STUDY OF THE STRENGTH OF THE OPEN WAGON HATCH DOOR WITH RECTANGULAR CORRUGATIONS UNDER STATIC LOADS

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Resume

Rail transport has been the leading sector of the whole transport network. In order to improve the efficiency of its functioning, it is important to develop measures that may help reduce the maintenance cost. To improve the open wagon hatch door strength, it is proposed to make it with rectangular corrugations. The results of calculations show that, taking into account the proposed solution, the weight of the improved hatch door is almost 10% lower than the weight of a typical one.

The strength of the hatch door under static loads was calculated. The results of calculations show that the strength of the hatch door under the diagrams considered is ensured.

The study will contribute to the development of best practices for modern structures of railway vehicles and increase their cost-effective operation.

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1 Introduction

The competitive struggle in the transport market makes it necessary to increase the efficiency of railway transport operation in order to maintain its leading positions [1-3]. It is known that one of the most common types of freight transported by rail is bulk cargo. It is transported in open wagons and unloaded through the discharge hatches (Figure 1), which form its floor, or by using mechanised unloading equipment.

A typical hatch door of an open wagon consists of a metal sheet to which strapping, locking brackets, and hinges are attached (Figure 2).

The sheet of a typical hatch door is a 5-mm thick metal plate with six longitudinal corrugations for higher rigidity (Figure 3).

It is important to note that under operating conditions, such a sheet does not have sufficient strength, and may be damaged (Figure 4).

The most common damages to the sheet are rupture and deformation, which cause the freight to spill out of an open wagon on the move, thus causing losses to the railway. In addition, these damages require additional capital investments due to unscheduled repairs of the wagon. In this regard, there is a need to develop measures aimed at improving the strength of the hatch door sheet under operating load conditions.

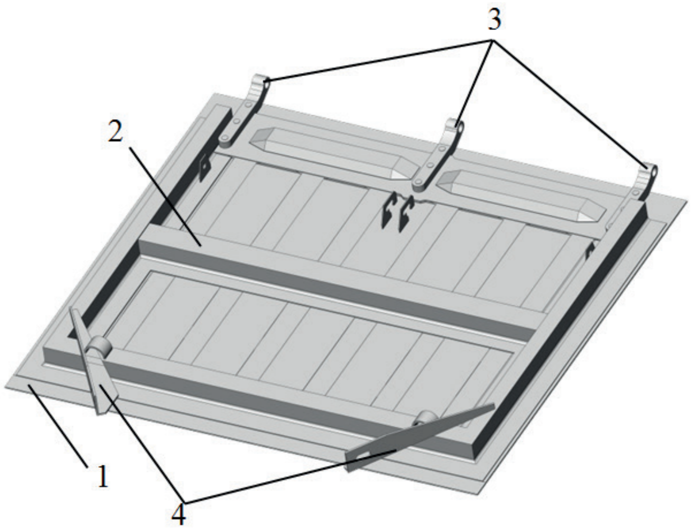
Analysing modern publications on improved hatch doors of open wagons, we have come to the conclusion that at present this problem is quite relevant. A new design of the hatch door for an open wagon with convex configuration is proposed in [4]. This design increases the payload of the open wagon by one tonne compared to the payload of standard hatch doors. This solution is scientifically justified. However, the authors considered only one design mode for the hatch door of an open wagon. Moreover, it is rather costly in manufacture and maintenance.

The hatch door proposed in [5] has similar disadvantages. It consists of two corrugated sheets with energy-absorbing material in-between. The strapping of the hatch door has a W-shaped profile. Although this hatch door design has certain advantages over standard ones, its widespread implementation is constrained by a number of factors.

To improve the strength of the hatch door, the authors of [6] propose to reinforce it with additional belts with the rectangular profile which facilitates the production and installation. The authors substantiate this hatch door design by means of strength calculations.

a) general view *b) unloading process*

Figure 1 *Open wagon with discharge hatches*



1 - sheet; 2 - strapping; 3 - locking brackets; 4 - hinges

Figure 2 *Hatch door of an open wagon*

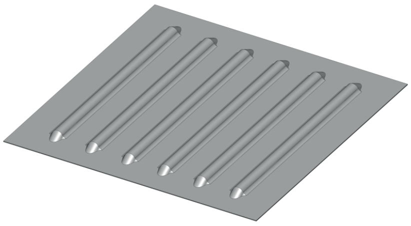


Figure 3 *Typical hatch door sheet*

a) rupture *b) deformation*

Figure 4 *Damage to the hatch door sheet*

However, this improvement increases the hatch door weight and, consequently, the wagon tare.

An improved hatch door reinforced with additional belts is also proposed in [7]. Here, the hatch door sheet is made of smooth sheet metal, and the reinforcing belts have the form of struts. The hatch door has moulded hinges. The study presents the calculations of the static strength for the hatch door, that confirm the feasibility of the proposed solution. However, widespread implementation of such hatch doors requires substantial capital investments.

To ensure the durability of the hatch door, materials with improved physical and mechanical properties, rather than steel, can be used for the door's components. For example, in [8], the authors propose to improve the wagon strength by using composite materials for the floor. The research proved the rationality of this solution. However, the authors did not consider the use of these materials in the hatch door for an open wagon.

Work [9] investigates the feasibility of using composite materials for the hatch door sheet for open wagons. The results of strength calculation of the hatch door proved the possibility of this implementation. However, these materials will increase the production costs, moreover, this will require an appropriate maintenance and repair system.

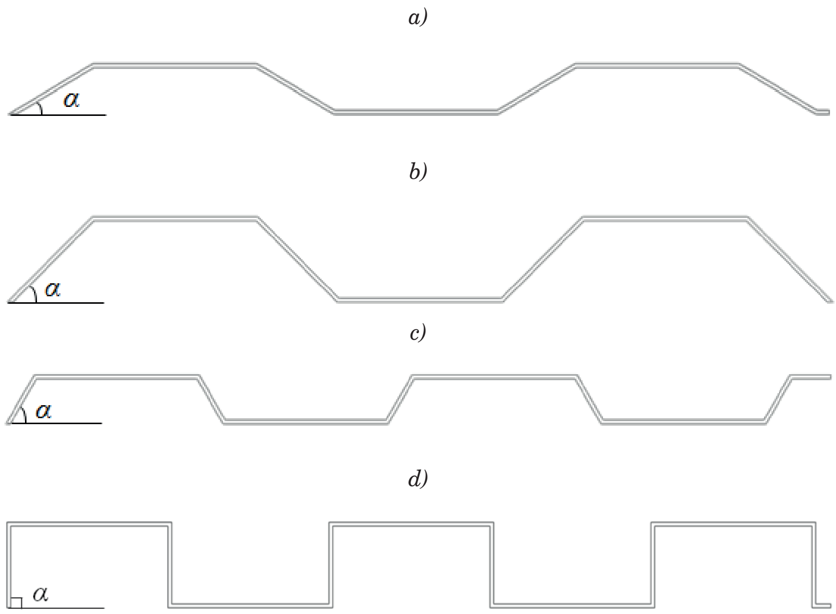
An improved hatch door for an open wagon is also proposed in [10]. Its structural feature is sandwich-type components. The hatch door consists of two smooth sheets with an energy-absorbing material in-between. The strapping has the Ω-shaped profile. The strength is calculated under static and dynamic loads on the hatch door. However, among the disadvantages of this hatch door are high cost, complexity of maintenance, etc.

The analysis of publications has shown that the issue of how to improve the hatch door of an open wagon is relevant and requires extensive research. The purpose of this study is to scientifically substantiate the design of the hatch door for an open wagon and determine the main strength indicators under static loads.

2 Materials and methods

Higher strength of the hatch door of an open wagon can be achieved by increasing the rigidity of the door. For this purpose, several possible variants of corrugations were studied and different corrugation angles were taking into account (Figure 5).

The moment of resistance depends on the corrugation profile (Table 1) and for rectangular corrugations it is the highest.



a) α = 30°; b) α = 45°; c) α = 60°; d) α = 90°

Figure 5 *Different corrugations of the sheet*

Table 1 *Inertia moments and resistance moments of cross-sections of the sheet*

Corrugation angle (α)	Moment of inertia (I), mm^4	Moment of resistance (W), mm^3
30°	$3.79 \cdot 10^4$	$3.64 \cdot 10^3$
45°	$12.52 \cdot 10^4$	$6.95 \cdot 10^3$
60°	$4.66 \cdot 10^4$	$4.48 \cdot 10^3$
90°	$19.53 \cdot 10^4$	$10.85 \cdot 10^3$

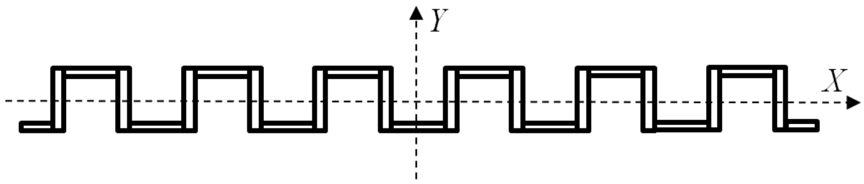


Figure 6 *Cross-section of the hatch door sheet*

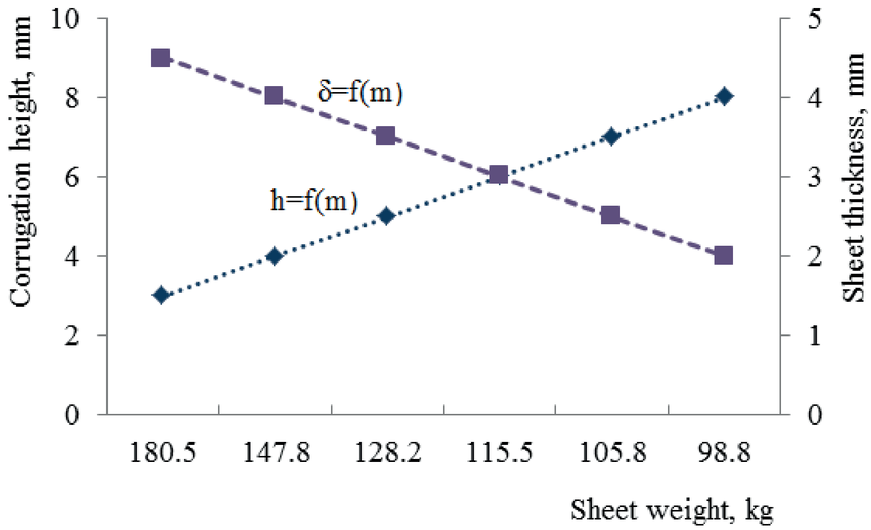


Figure 7 *Dependence of the sheet weight on its parameters*

Therefore, this study deals with the feasibility of rectangular corrugations for the hatch door used in open wagons.

The geometrical parameters of sheet corrugations are determined provided that its moment of inertia is higher than that of a typical hatch door sheet (W= 200.8 $\cdot$ 10^3 mm^3).

The moment of resistance of the sheet is determined by dividing its cross-section into elementary rods (Figure 6).

Here, the moment of resistance is calculated based on the known moment of inertia. Thus, for a vertical rod [11-12] it is:

$$W = \frac{2 \cdot I}{h}, \tag{1}$$

where h is the rod height.

Herewith,

$$I = \frac{\delta \cdot h^3}{12}, \tag{2}$$

where δ is the rod width.

The rational parameters of corrugations are determined with variational calculations. The target function of these calculations is the minimum weight of the sheet with such variational parameters as the corrugation height h and the corrugation thickness δ.

The calculation has the following constraint: the moment of inertia of the sheet must be higher than that of a typical sheet.

The moment of resistance is determined by Equation (1). The sheet weight is calculated using the sheet volume. The calculation results are shown in Figure 7.

An analysis of Figure 7 shows that a rational solution is corrugations with a height of h = 60 mm and a thickness of δ = 3 mm. The total sheet weight is about 110 kg. Importantly, the calculated sheet weight is almost 10% lower than the weight of a typical sheet.

3 Results

The strength of the hatch door sheet with rectangular corrugations is studied by means of the spatial model built in SolidWorks [13-14] (Figure 8).

The strength of the hatch door is determined using the FEM in SolidWorks Simulation [15-17]. The model is built with tetrahedra (Figure 9), the number of which is determined graphically and analytically [18-20]. Thus, the finite element model has 180,572 elements and 566,450 nodes.

The strength is calculated based two design diagrams [21]:

- the effect of a uniformly distributed load of 69.9 kN on the hatch door area; this force includes the gross weight force of the hatch door and the dynamic load (diagram I); and
- the effect of a load of 50 kN distributed in the hatch door centre across an area of 250x250 mm (diagram II).

a) view one b) view two

Figure 8 *Spatial model of the hatch door*

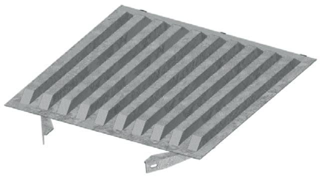
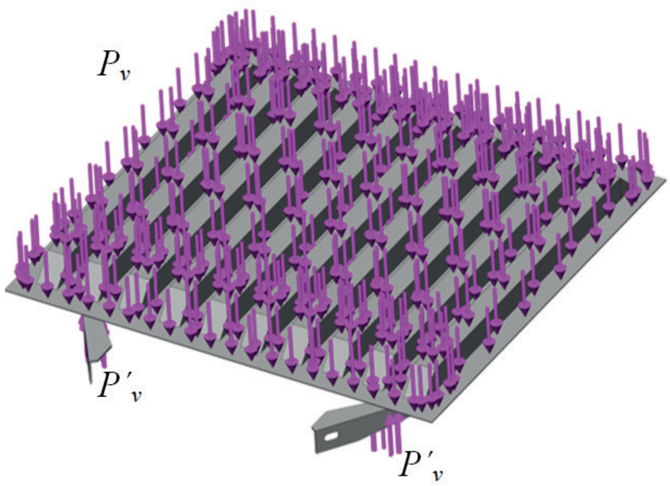


Figure 9 *Finite element model of the hatch door*



(Load diagram I)

Figure 10 *Design diagram of the hatch door*

The design diagram of the hatch door under the action of the evenly distributed load P_v is shown in Figure 10.

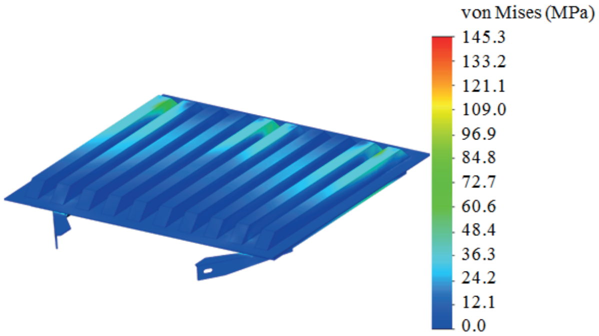
The hatch door is secured with the hinges, and the locking brackets are subject to the reactions P'_v to the vertical load P_v. The hatch door is made of Steel 09G2S.

The calculation results are shown in Figures 11-13. The maximum stresses in the hatch door are 145.3 MPa (Figure 11). However, they are lower than permissible by 30% [21]. This means that the safety factor of the hatch door is about 1.4 under specified load conditions. It should be noted that the resulting stresses in the hatch door are 23% lower than those in a typical structure. From Figure 12 it can be seen that the maximum stresses occur in the areas of interaction between the hinges and the strapping, because the model is secured by the hinges, and the load is applied to the sheet and the locking brackets.

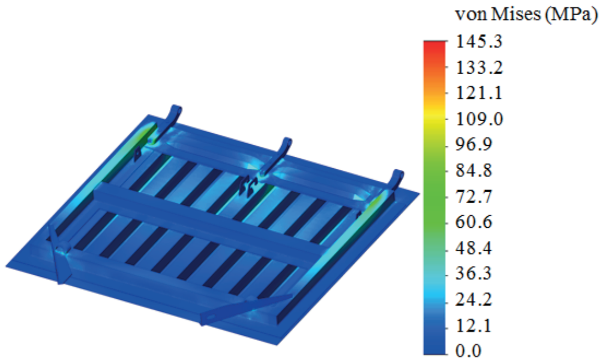
The maximum displacements in the hatch door occur in the locking brackets and amount to 2.27 mm (Figure 13). This distribution of displacement fields can be explained by the fact that the vertical reactions to the load P_v on the sheet are applied to the middle part of the bracket, while the end part of the bracket is free.

The following stage of the study included the determination of the hatch door strength under the vertical load P_v distributed in the centre across an area of 250x250 mm, which is equal to 50 kN. The design diagram of the hatch door is shown in Figure 14. The reactions P'_v to the vertical load P_v are applied to the locking brackets.

The results of calculations for the hatch door are shown in Figures 15-17. The maximum stresses are 161.5 MPa (Figure 15); they are 23% lower than permissible [21]. The safety factor of the hatch door under specified load conditions is 1.3. The resulting



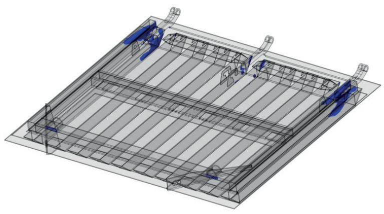
a) view one;



b) view two

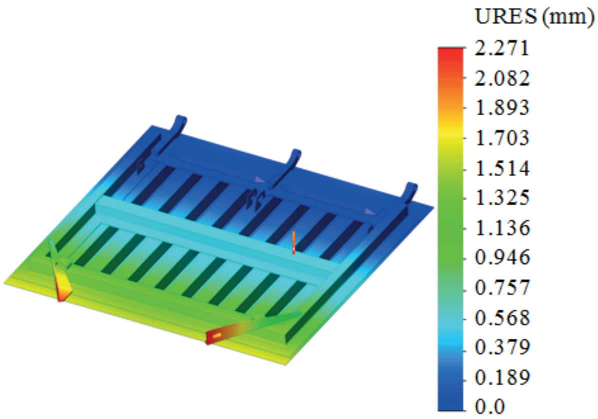
(Load diagram I)

Figure 11 *Stress state of the hatch door*



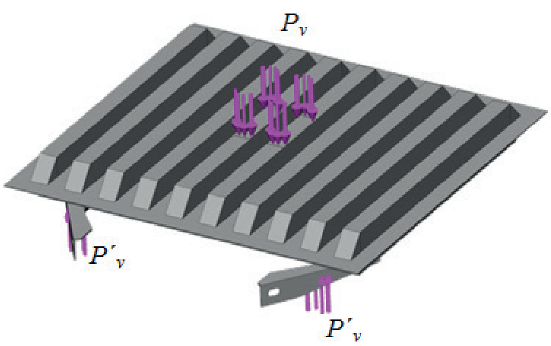
(Load diagram I)

Figure 12 *Most loaded areas of the hatch door*



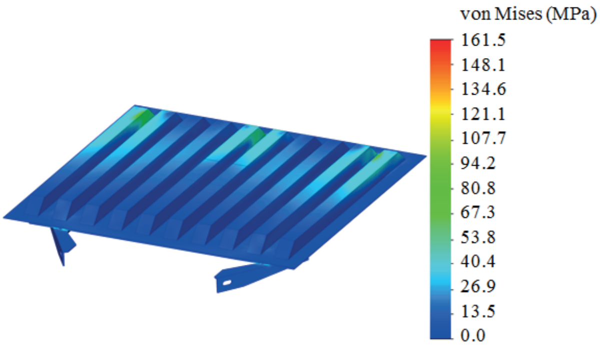
(Load diagram I)

Figure 13 *Displacements in the hatch door*

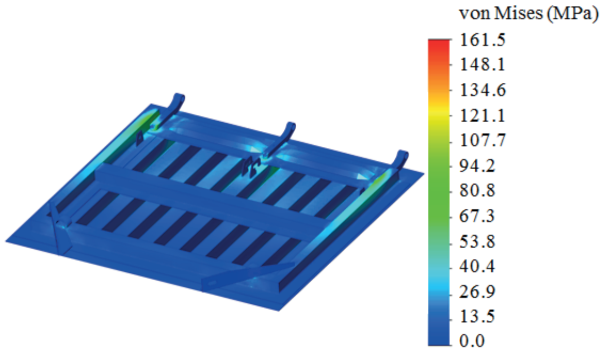


(Load diagram II)

Figure 14 *Design diagram of the hatch door*



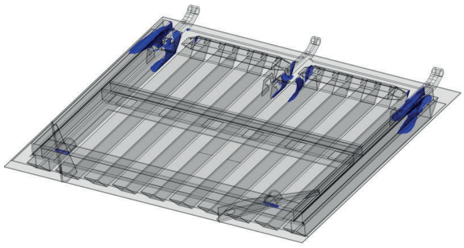
a) view one;



b) view two

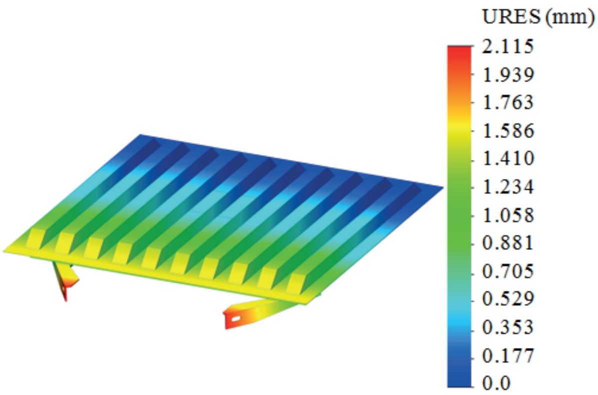
(Load diagram II)

Figure 15 *Stress state of the hatch door*



(Load diagram II)

Figure 16 *Most loaded areas of the hatch door*



(Load diagram II)

Figure 17 *Displacements in the hatch door*

stresses in the hatch door are 23.5% lower than those in a typical structure. The maximum stresses are also concentrated in the areas of interaction between the edge hinges and the strapping. This is explained in the same way as for design diagram I.

The maximum displacements in the hatch door occur in the locking brackets (Figure 17); they amount to 2.1 mm. This distribution of displacement fields can be explained in the same way as for the previous design diagram.

The research shows that, taking into account the proposed improvement, the hatch door strength under the static loads is ensured.

4 Discussion

In order to increase the strength of the hatch door for an open wagon, it is proposed to use rectangular corrugations to improve the hatch door sheet. In addition, possible corrugation profiles for the hatch door sheet are analysed (Figure 5). It is found that the cross-section of the sheet with rectangular corrugations has the maximum moment of resistance (Table 1). The geometrical parameters of corrugations are determined by means of the moment of resistance of the cross-section of the sheet. The results of calculations demonstrate that corrugations with a height of h=60 mm and a thickness of δ = 3 mm are a rational solution. The sheet weight is about 110 kg, which is almost 10% lower than the weight of a typical sheet (Figure 7).

The following stage of the calculation included the determination of the main strength indicators of the hatch door under static loads, namely, the action of a load of 69.9 kN uniformly distributed on the hatch door and the action of a load of 50 kN distributed in the centre of the hatch door on an area of 250x250 mm.

The calculation results show that the hatch door strength is ensured under the load diagrams in question. The maximum stresses in the hatch door are 145.3 MPa for load diagram I (Figure 11). These stresses are lower than permissible by 30%. The maximum displacements in the hatch door occur in the locking brackets and are 2.27 mm (Figure 13).

The maximum stresses in the hatch door at load diagram II are 161.5 MPa and they are lower than permissible by 23% (Figure 15). The maximum displacements in the hatch door occur in the locking brackets and they amount to 2.1mm (Figure 17). Therefore, the hatch door strength under static loads is ensured.

The restriction of this study is that the strength calculation of the hatch door included a rigid interaction between the hinges and the centre sill of an open wagon.

Moreover, it did not include the welds between the individual components of the hatch door. Thus, the hatch door was considered monolithic.

The advantage of this study in comparison with [4] is that the technical maintenance of the improved hatch door can be carried out at existing repair enterprises. Unlike the hatch door designs presented in [5, 7-10], the design proposed is less expensive in production thanks to lower costs of the structural materials used. In addition, unlike the solution described in [6], the proposed hatch door design does not increase the open wagon tare.

It is important to note that the proposed improved hatch door can be not only manufactured but also modernized at wagon building and repair enterprises.

The further research of the authors may include the determination of the hatch door strength under dynamic loads and experimental research into the hatch door strength.

5 Conclusions

1. The geometrical parameters of the corrugations of the hatch door of an open wagon are determined using the moment of resistance of the cross-section, the sheet being considered as a set of rods. The calculation results show that the corrugations with a height of h =60 mm and a thickness of δ =3 mm is a rational solution. The sheet weight is about 110 kg, which is almost 10% lower than the weight of a typical sheet.
2. The strength of the hatch door for an open wagon under static loads is calculated. The calculation results show that the maximum stresses in the hatch door are 145.3 MPa when it is subject to a load evenly distributed across its area; they are 30% lower than permissible. It is important to note that the calculated stresses are 23% lower than those in a typical structure. The safety factor of the hatch door is about 1.4. The maximum displacements occur in the locking brackets and are 2.27mm.

The calculation results show that the maximum stresses in the hatch door are 161.5 MPa under a vertical load distributed in its centre across an area of 250x250 mm; they are 23% lower than permissible. The stresses obtained are 23.5% lower than those in a typical structure; the safety factor is 1.3. The maximum displacements in the hatch door are 2.1 mm and occur in the locking brackets. Using the results obtained it can be concluded that the strength of the hatch door subjected to static loads is ensured.

The research will contribute to the development of best practices for modern designs of railway vehicles and increase their operational efficiency.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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